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Trends and establishment of shell effects in (n, d), (n, t) and (n, ^{3}He) reaction cross sections around 14 MeV

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Abstract : The systematic behaviour of (n, d), (n, t) and (n, ^{3}He) reaction cross sections has been studied around 14 MeV neutron energy. The empirical relations for these reaction cross sections have been obtained, which show fairly good fits with the experimental values. The shell effects have been established at magic nucleon numbers for (n, d), (n, t) and (n, ^{3}He) reaction cross sections at 14 MeV neutron energy. The odd-even effects have also been observed, as the cross sections of odd-mass nuclei are higher than their neighbouring even-even nuclei.

Keywords : Cross section, shell effect, odd-even effect, magic number

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1. Introduction

A study of the systematics of (n, d), (n, t) and (n, ^{3}He) reactions has been carried out and some of the observed trends in reaction cross sections are described. A survey of the existing data [1–20] on the (n, d), (n, t) and (n, ^{3}He) reaction cross sections around 14 MeV neutron energy shows that the experimentally reported values for medium and heavy mass nuclei are very scarce and even when they exist, they are often contradictory *e.g.* concrete values have been reported, which are in gross disagreement with each other. In a number of cases, only one cross section value has been reported for one isotope. These reported values vary from few tens of microbarns to a few millibarns. Thus, the neutron induced (n, d), (n, t) and (n, ^{3}He) reactions are considered 'rare' due to their small reaction cross section values. Hence, the measurements are rather difficult due to the low induced activities. Also, the measured cross section values are not available for some elements. For many practical purposes like thermo-nuclear devices, fusion reactors design, such reaction cross sections are needed.

Theoretical calculations depend upon the established complicated nuclear models. Therefore, it will be worthwhile to analyse systematics of such nuclear reaction cross sections, to formulate empirical relations to predict such cross sections when experimental results are not available or are not amenable to measurements due to experimental problems.

In the present work, the experimentally reported (n, d) [1–6], (n, t) [6–15] and (n, ^{3}He) [6,14–20] reaction cross sections from various laboratories have been reviewed and systematic empirical relations have been obtained around 14 MeV neutron energy, which can be helpful for estimating unknown cross sections. Also, the shell effects have been observed in (n, d), (n, t) and (n, ^{3}He) reaction cross sections at magic nucleon numbers mainly at Z or N = 20, 28, 50 and 82.

2. Formulation and discussion

(i) (n, d) reaction :

The values of (n, d) reaction cross sections for the present investigation have been taken from the existing data of Grimes *et al* [1–3] and IAEA report [6] around 14 MeV neutron energy for $22 \le Z \le 75$. For this region, the (n, d) reaction cross sections depend upon Z/A as an exponential function of Z/A. The empirical relation for (n, d) reaction cross sections for nuclei having Z/A in the range $0.39 \le Z/A \le 0.48$ ($22 \le Z \le 75$) is given by

$$\sigma_{\mathrm{n,d}} = a \exp(b\ Z/A) \quad \text{(mb)}, \tag{1}$$

where $a = 1.11407 \times 10^{-8}$ and $b = 44.759$.

The plot of $\sigma_{\mathrm{n,d}}$ *versus* Z/A is shown in Figure 1(a). A semilog plot of the ratio of experimental cross sections to predicted cross sections [above eq. (1)] *versus* Z/A is given in Figure 1(b), which shows that the predicted cross sections are in good agreement with the

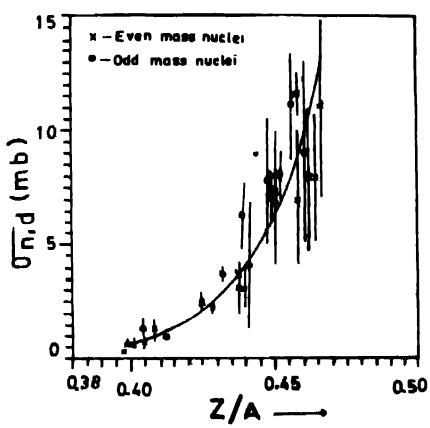

Figure 1(a). Plot of $\sigma_{\mathrm{n,d}}$ *versus* Z/A.

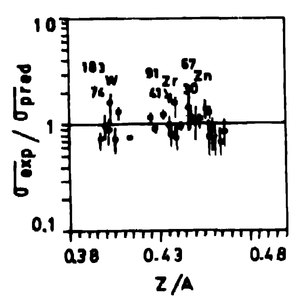

Figure 1(b). Comparison of predicted (n, d) cross sections with experimental values.

experimental values within ± 28% whereas experimental errors in these cross sections exist from 5 to 40%. There are a few exceptions like $^{67}_{30}Zn_{37}$, $^{91}_{40}Zr_{51}$ and $^{183}_{74}W_{109}$ with larger deviations for which the cross sections cannot be predicted by this method with even above accuracy, which are difficult to explain.

As there is a large spread in the cross sections of $\sigma_{n,d}$ *versus* Z as shown in Figure 1(c), so for formulating the empirical relation for $\sigma_{n,d}$ *versus* Z/A was found to be more suitable.

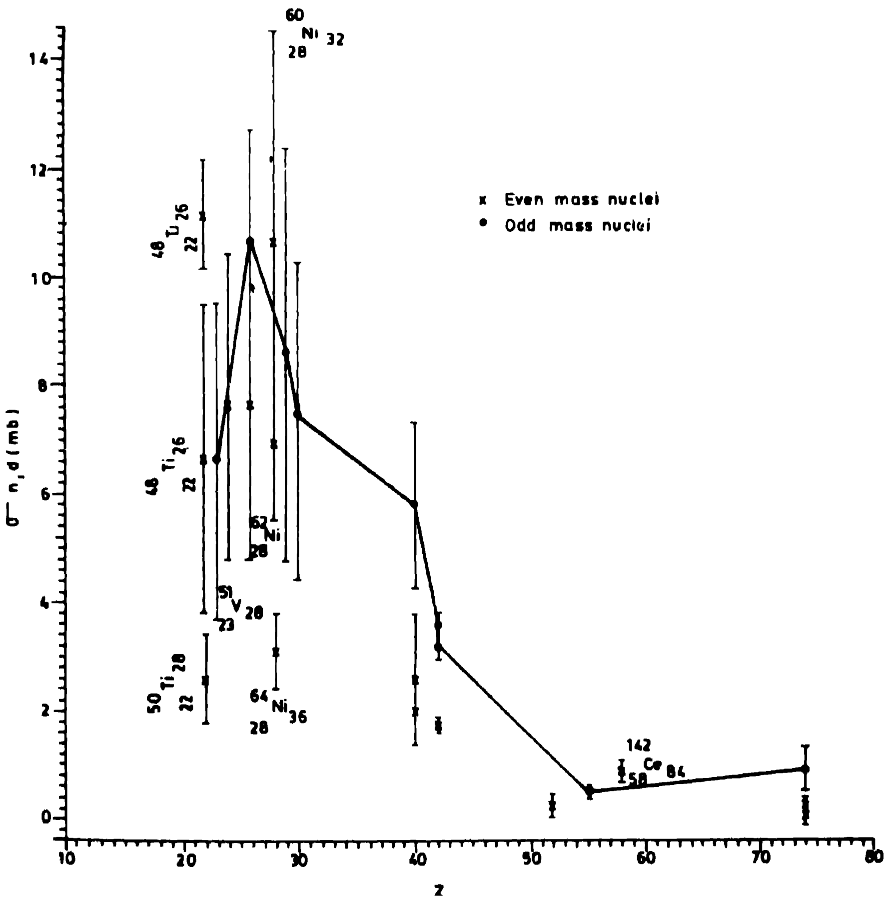

Figure 1(c). Plot of $\sigma_{n,d}$ *versus* Z.

The odd-even nuclei have higher cross sections than even-even nuclei and this odd-even effect is distinctly marked when neutron excess is small *i.e.* for lighter nuclei. Figure 1(c) of $\sigma_{n,d}$ *versus* Z shows more clearly the odd-even effects with the exception of the isotope ${}^{48}_{22}Ti_{26}$ while the other isotope ${}^{50}_{22}Ti_{28}$ follows the expected behaviour of very low cross section being an even-even isotope with magic neutron number $N = 28$. It is interesting that the other measurement of ${}^{48}_{22}Ti_{26}$ as depicted in the figure follows the expected odd-even systematics. The cross section of odd-even isotope ${}^{51}_{23}V_{28}$ is lower than the neighbouring isotopes, as it has magic neutron number. The isotope $^{60}_{28}Ni_{32}$ has very large experimental error and needs no serious consideration though being a magic proton number isotope, while other isotopes $^{62}_{28}Ni_{34}$ and $^{64}_{28}Ni_{36}$ follow distinctly the magic proton number effect. The heavier isotope $^{142}_{58}Ce_{84}$ is a bit off the expected trend but the cross sections for such heavier nuclei are very small and experimental errors cannot be ruled out.

The shell effects in $\sigma_{n,d}$ at magic nucleon numbers Z and N are shown in Figure 2. The shell effect is distinct at Z = 20, 28 and at N = 28. At nucleon numbers 50 and 82 no shell effect is demonstrated due to non-availability of data.

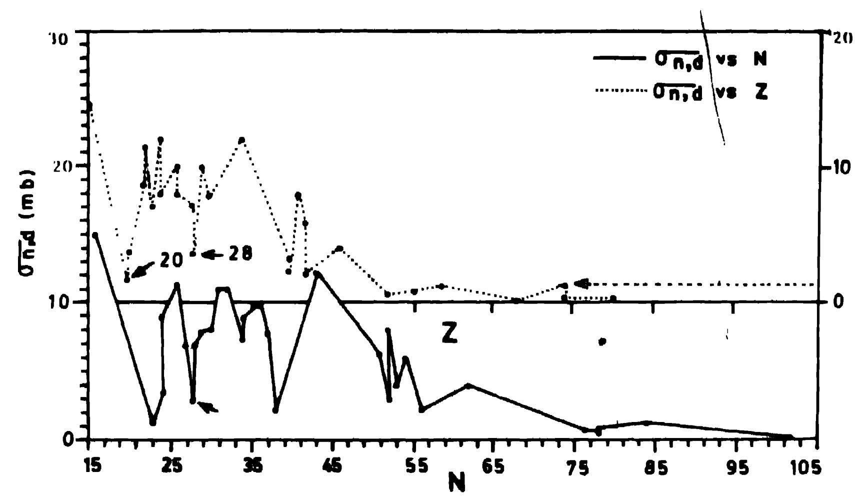

Figure 2. Plot of $\sigma_{n,d}$ *versus* Z and N (arrows indicate the magic nucleon numbers).

(ii) (n, t) reaction :

The experimental data of (n, t) reaction cross sections at about 14 MeV neutron energy for 12 $\leq Z \leq 92$ have been collected from the literature [6–15]. The selected data were already processed by the method of the weighted average [13]. The semilog plot of the averaged cross sections $\sigma_{n,t}$ as a function of proton number (Z) is shown in Figure 3(a) for even-even and odd-mass nuclei. The empirical relation obtained for (n, t) reaction cross sections is given by

$$\sigma_{n,t} = a \exp(-bZ) \quad (\mu\text{barn}) \tag{2}$$

for even-even nuclei having $23 \leq Z \leq 92$,

$$a = 91.6242 \text{ and } b = 0.01312;$$

and for odd-mass nuclei having $13 \leq Z \leq 60$,

$$a = 2547.07 \text{ and } b = 0.04247.$$

As depicted in Figure 3(a), $^{40}_{20}Ca_{20}$ being doubly magic nucleus and $^{139}_{57}La_{82}$ with magic neutron number have small values of cross sections. The cross section of the other odd-mass nucleus $^{205}_{81}Tl_{124}$ is small as it has a heavy mass and the cross sections of heavy mass nuclei are smaller due to Coulomb barrier and large neutron excess. The odd-even effect is clear from this figure as the cross sections for odd-mass nuclei are higher than for their neighbouring even-even nuclei. Except for the lightest nuclei the Coulomb barrier is in all cases higher than the energy of tritons emitted in (n, t) reactions at 14 MeV, and this energy difference seems to govern dominantly the cross section values. This concept is verified by the data in Figure 3(a), as the threshold energies of (n, t) reactions are higher for even-even

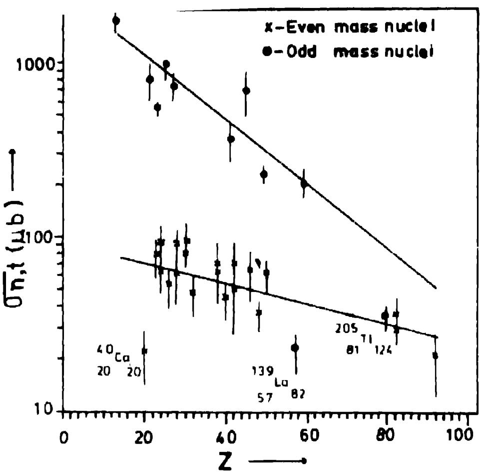

Figure 3(a). Semilog plot of $\sigma_{n,t}$ *versus* Z.

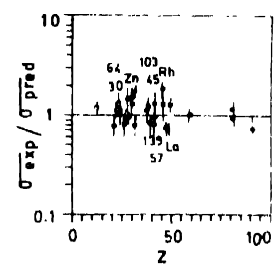

Figure 3(b). Comparison of predicted (n, t) cross sections with experimental values.

nuclei than for odd-mass nuclei. The (n, t) reaction being one neutron one proton pick-up reaction so the odd-even effects are prominent in case of (n, t) reaction cross sections. The slope for the odd-mass nuclei is more, hence in the heavy mass region, the cross sections for even-even and odd-mass nuclei do not differ much. It is noticed that with the increase in Z, the difference in the Q-values is very small. The odd-even effects decrease gradually and finally disappear. It is seen from Figure 3(b) that the empirical relations give good fits with the experimental values within ± 25% except for the few cases as $^{64}_{30}Zn_{34}$, $^{103}_{45}Rh_{58}$ and $^{139}_{57}La_{82}$ whereas experimental errors are about 10–30%.

Figure 4 shows the shell effects in $\sigma_{n,t}$ at magic nucleon numbers. The shell effects at Z = 20, 28, 82 and N = 20, 28, 50 are clearly depicted here. At Z = 50 and N = 82 the trend shows one sided minimum due to non-availability of data points on the right hand side of Z = 50 and N = 82.

(iii) (n, ³He) reaction :

The neutron induced (n, ^{3}He) reaction cross sections around 14 MeV neutron energy are reviewed [6,14–20] for the isotopes with 13 ≤ Z ≤ 82. As (n, ^{3}He) cross sections have so far been measured for a very small number of isotopes, only the available data is depicted here.

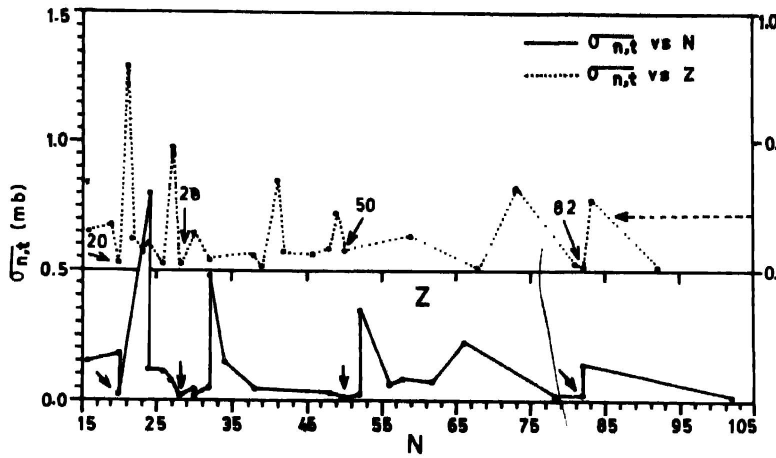

Figure 4. Plot of $\sigma_{n,t}$ *versus* Z and N (arrows indicate the magic nucleon numbers)

The dependence of (n, ^{3}He) reaction cross sections on proton number Z is shown in Figure 5(a) by a polynomial curve of degree 5. The empirical relation for the isotopes having $13 \leq Z \leq 82$ is given by

$$\sigma_{n},{}^3\text{He} = aZ^5 - bZ^4 + cZ^3 - dZ^2 - eZ + f \quad (\mu\ \text{barn}) \tag{3}$$

where $a = 4.243 \times 10^{-6}$, $b = 0.0009057$

$c = 0.0598$, $d = 0.30395$

$e = 102.078$ and $f = 2744.12$.

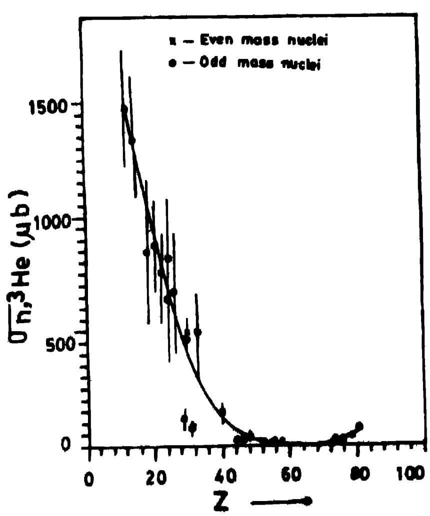

Figure 5(a). Plot of σ_n, ^{3}He *versus* Z.

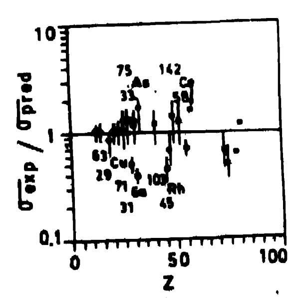

Figure 5(b). Comparison of predicted (n, ^{3}He) cross sections with experimental values.

A semilog plot of $\sigma_{exp}/\sigma_{pred}$ *versus* Z is given in Figure 5(b), which shows that the results are consistent with the available measured data satisfactorily within ± 30% whereas experimental errors are about 10–40%. There are a few exceptions which cannot be predicted by eq. (3) within this accuracy *e.g.* $^{63}_{29}$Cu, $^{71}_{31}$Ga, $^{75}_{33}$As, $^{103}_{45}$Rh and $^{142}_{58}$Ce.

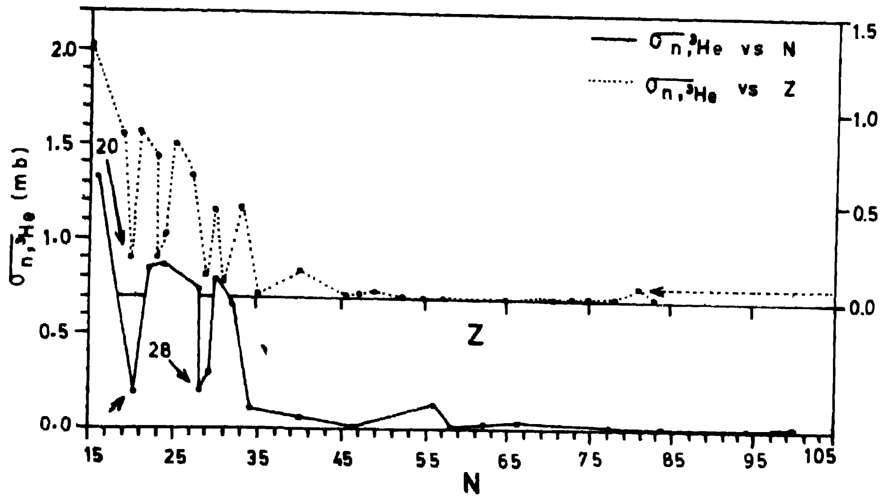

Figure 6. Plot of σ_n, ^{3}He *versus* Z and N (arrows indicate the magic nucleon numbers).

The shell effects at $Z = 20$ and at $N = 20$, 28 are depicted in Figure 6. The shell effects at other magic nucleon numbers cannot be predicted due to lack of measured available data in this range. There are only a few data points for even-even nuclei for σ_n, ^{3}He at 14 MeV, so no definite conclusion regarding odd-even effects can be predicted.

3. Conclusion

The measured data of (n, d), (n, t) and (n, ^{3}He) reaction cross sections are scarce so the new empirical relations given by eqs. (1) – (3) are very useful for the quick estimation of the cross sections, where the experimental data are not available as well as in testing new experimental results. As the uncertainties in the experimental values are quite large, it is troublesome and difficult to evaluate them to a higher accuracy. A comparison of the predicted cross sections with experimental values, as shown in Figures 1(b), 3(b) and 5(b) reveals that the agreement is quite satisfactory. There are a few exceptions which cannot be predicted by these formulae even, with above accuracy, which are difficult to explain.

The shell effects in (n, d), (n, t) and (n, ^{3}He) reaction cross sections have been predicted at magic nucleon numbers. In a few cases the shell effects cannot be predicted due to non-availability of data points. The odd-even effects have also been observed as the cross sections of odd-mass nuclei are higher than their neighbouring even-even nuclei.

In the heavy mass region, the odd-even effect is diluted since with the increase in Z, the difference in Q-values of odd-mass and even-even nuclei gets smaller and neutron excess becomes larger *etc*. So, the odd-even effects decrease gradually and finally disappear. The (n, t) reaction is one neutron and one proton pick-up reaction as compared to the single proton pick-up in (n, d) and two protons pick-up in (n, ^{3}He) reactions. It seems to contribute to the enhanced odd-even effects in (n, t) cross sections.

The previous investigations of the (n, t) reaction cross sections as a function of the asymmetry parameter $(N-Z)/A$ have been described by several authors [10,21] at 14–15 MeV without showing shell and odd-even effects. Dökmen and Atasoy [22] have shown trends and an empirical relation for (n, t) cross sections around 14 MeV without showing shell effects.

The systematics of (n, d), (n, t) and (n, ^{3}He) reactions with Z/A or Z zeems more reasonable than with $(N-Z)$ or $(N-Z)/A$ because these are one or two nucleon pick-up reactions. For (n, t) reaction, the systematics with neutron excess $(N-Z)$ or asymmetry parameter $(N-Z)/A$ is partially justified because (n, t) is one neutron one proton pick-up reaction, but this should not be valid for (n, d) and (n, ^{3}He) reactions.

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